

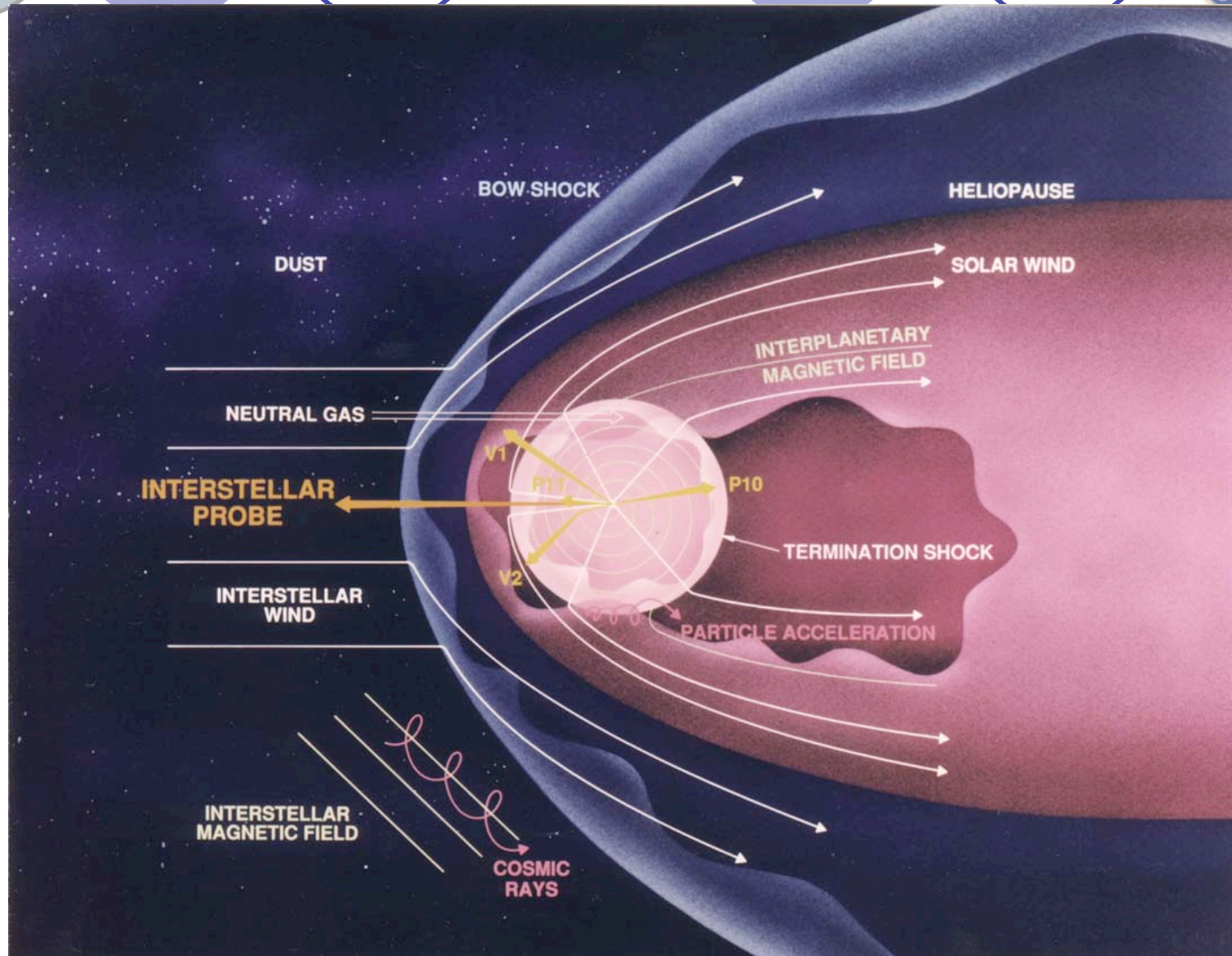
# **The Solar Wind as an Astrophysical Laboratory: A Review of Pickup Ions**

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# The Heliosphere





# Ions in the Heliosphere



- Close to the Sun nearly all ions are of solar origin
- Further out in heliosphere, ions of other origins start to play larger role and mix in with solar wind
- At the terminations shock, non-solar ions account for 10% of the population
- Sources of non-solar ions include
  - Interstellar gas and grains
  - Interplanetary grains
  - Local sources: comets, planets, asteroids
- Non-solar ions start as neutral atoms which become ionized and are “picked up” by the solar wind



# Detecting Ions in the Heliosphere



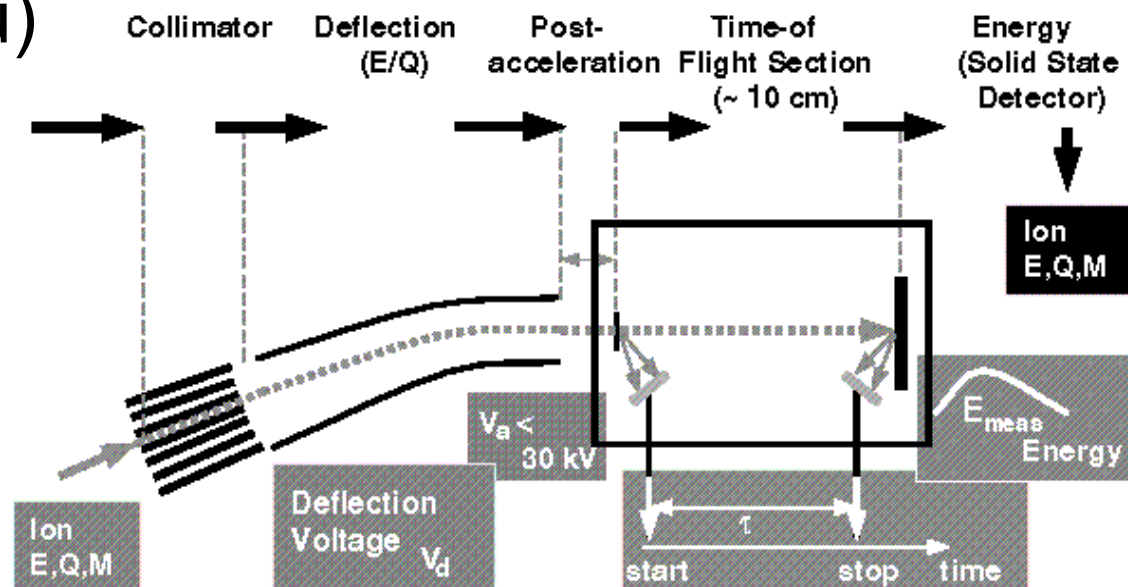
- Interstellar hydrogen originally observed in Ly-alpha background maps (Bertaux and Blamont, 1971; Thomas and Krasse, 1971)
- Solar Wind Ion Composition Spectrometers (SWICS) on Ulysses provided numerous direct measurements of interstellar pickup ions (PUIs)
- Ion mass spectrometers allow separation and identification of solar wind ions and PUIs, e.g.,
  - $^4\text{He}^+$  at 1AU (Mobius et al. 1985)
  - $\text{H}^+$  (Gloeckler et al., 1993)
  - $3\text{He}^{++}$  (Gloeckler and Geiss, 1996)
  - $4\text{He}^{++}$  (Gloeckler et al. 2000a)
  - Heavier PUIs (Geiss et al., 1994, 1996)



# SWICS Principle of Operation

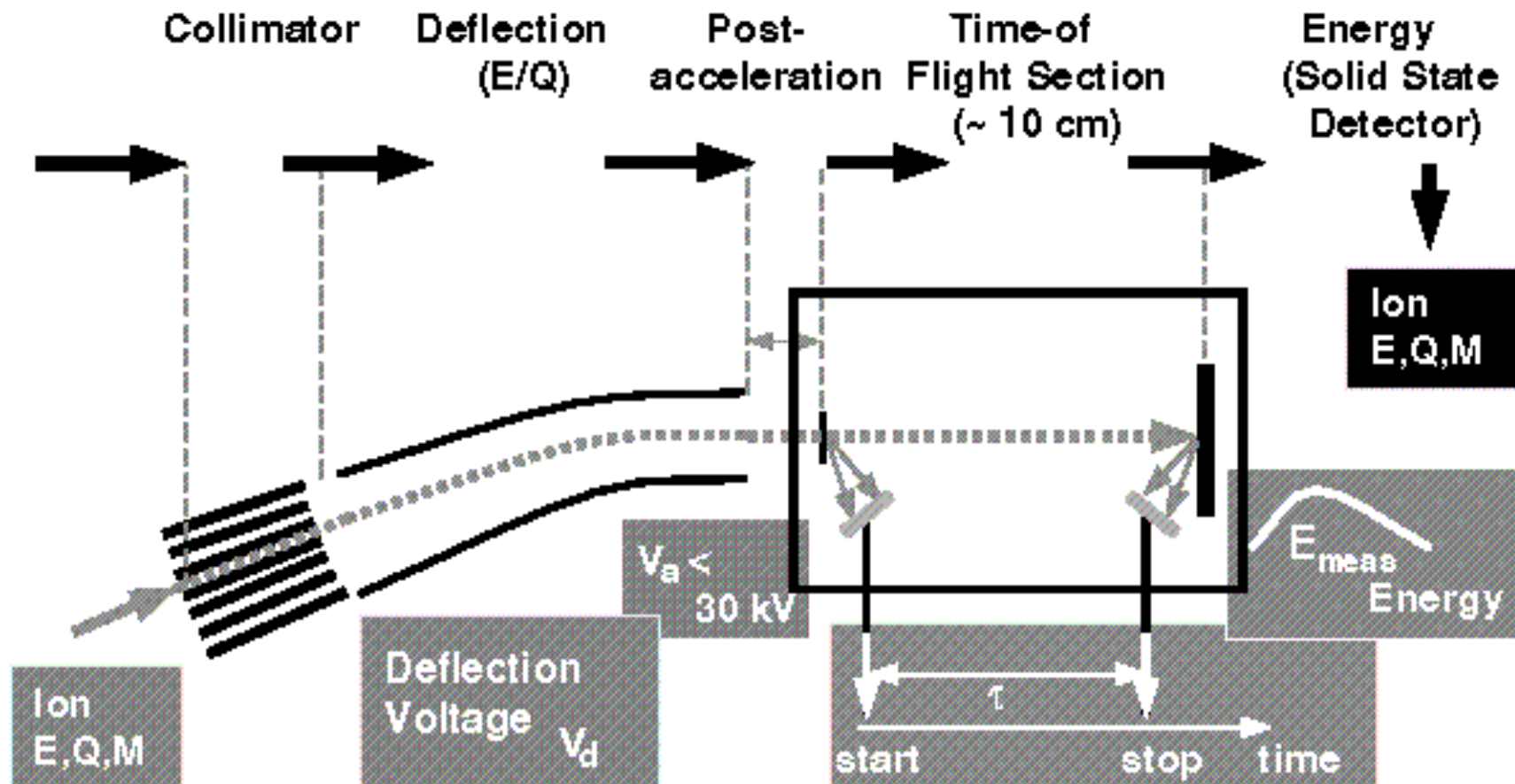


- Sensor counts particles as a function of energy per charge (velocity) and total energy, uses time of flight to obtain
  - Mass, mass per charge, and velocity
- Obtain velocity distribution functions for various ions (1-60 amu)
- Identifies over 40 ions: H, He, C, (N), O, (S), Si, Mg, Fe
- Also ACE/SWICS at 1AU



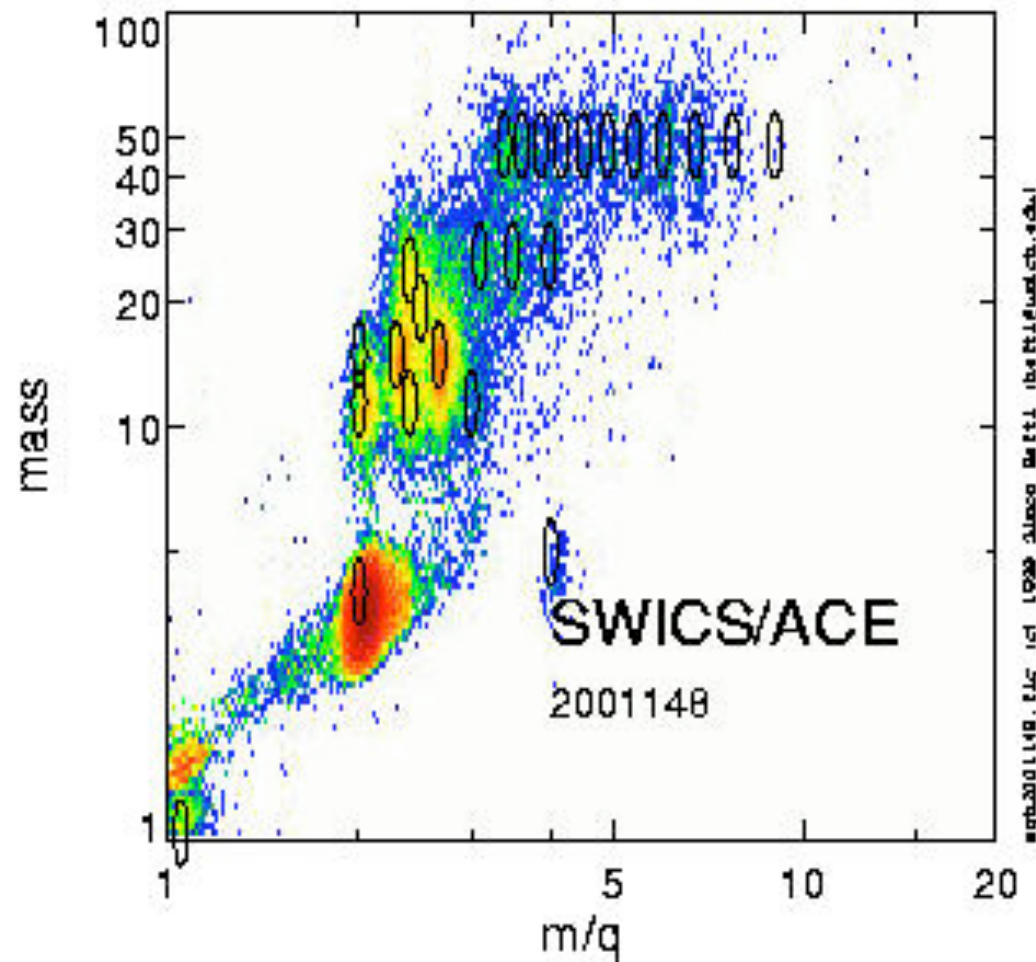


# SWICS Principle of Operation





# SWICS Principle of Operation



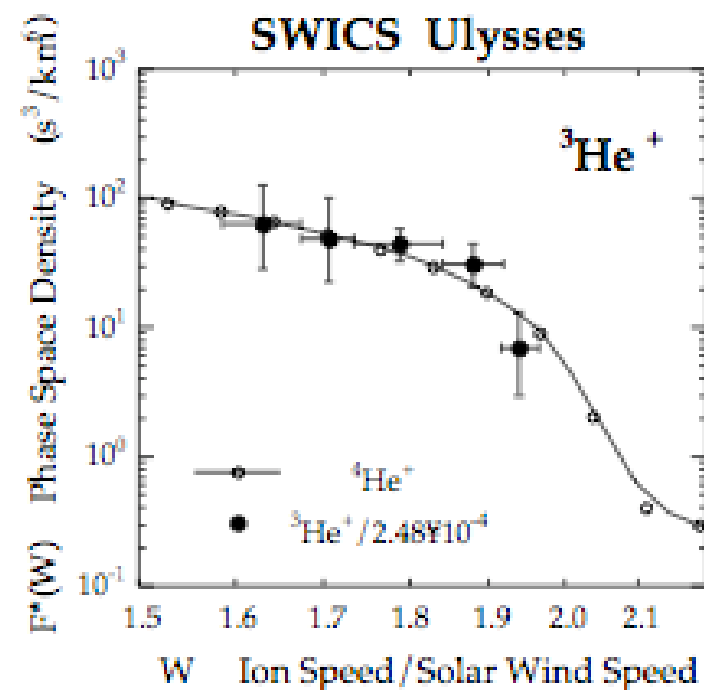
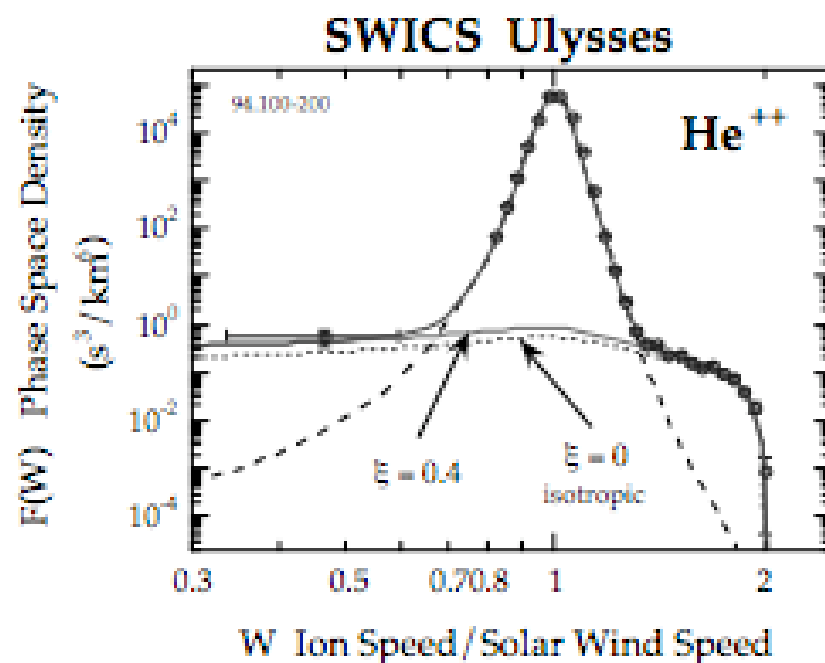
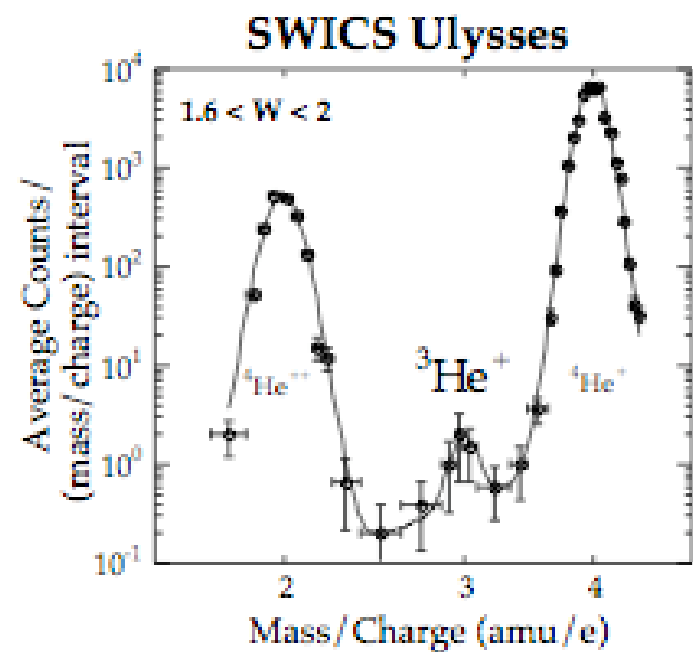
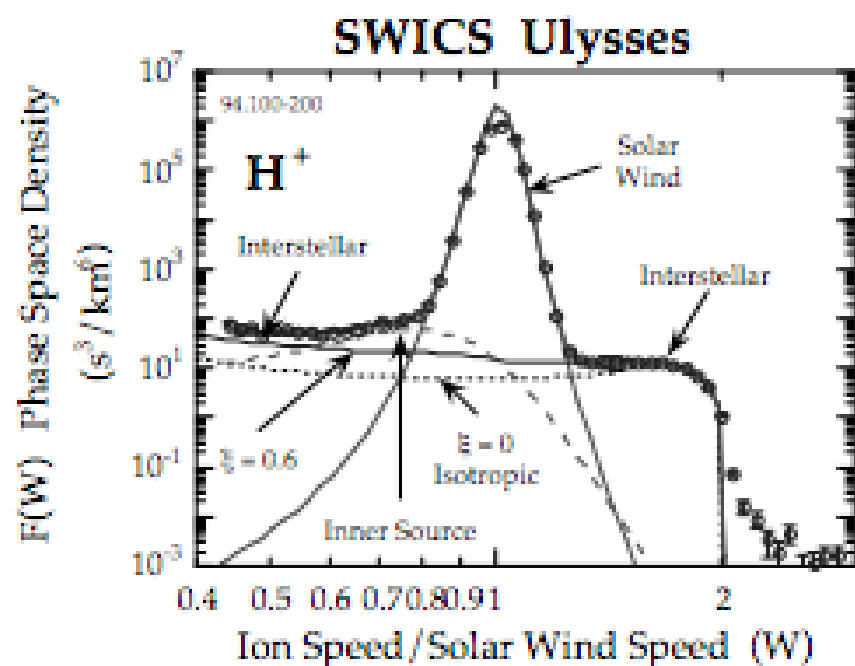


# Measuring Ions in the Heliosphere



In undisturbed solar wind conditions, measure two distinct ion velocity distributions in the heliosphere

- Solar wind ions
  - narrow mach angle; dominate the spectrum
- PUIs from non-solar sources
  - less abundant and have a broad suprathermal velocity distribution function
  - $w = v_{\text{ion}}/v_{\text{sw}}$  in spacecraft reference frame,
  - $\mathbf{w} = (\mathbf{v}_{\text{ion}} - \mathbf{v}_{\text{ion}})/v_{\text{sw}}$ , in solar wind reference frame





# Ions from Solar Sources



- Solar corona is  $\sim 10^6$  K
- High charge state ions are created in the corona, including  $\text{He}^{2+}$ ,  $\text{O}^{6+}$ ,  $\text{Fe}^{10+}$ ,  $\text{C}^{5+}$ , etc.
- These ions “freeze-in” within 3 - 4 solar radii and are carried out by solar wind
- Charge states persist throughout the heliosphere

VON STEIGER ET AL.: SOLAR WIND COMPOSITION

**Table 1.** Abundance Ratios Relative to Oxygen Obtained With Ulysses/SWICS During the Four  $\sim 300$ -Day Periods Defined in Plate 1<sup>a</sup>

	FIP	“Max”	“South”	“North”	“Min”	Phot.
He	24.59	$95.9 \pm 35.1$	$72.7 \pm 7.9$	$73.6 \pm 8.2$	$84.0 \pm 33.0$	126
C	11.26	$0.670 \pm 0.071$	$0.683 \pm 0.040$	$0.703 \pm 0.037$	$0.670 \pm 0.086$	0.489
N	14.53	$0.069 \pm 0.038$	$0.111 \pm 0.022$	$0.116 \pm 0.021$	$0.088 \pm 0.035$	0.123
O	13.62	$= 1 \pm 0$	$= 1 \pm 0$	$= 1 \pm 0$	$= 1 \pm 0$	$= 1$
Ne	21.56	$0.091 \pm 0.025$	$0.082 \pm 0.013$	$0.084 \pm 0.013$	$0.104 \pm 0.027$	0.178
Mg	7.65	$0.147 \pm 0.045$	$0.105 \pm 0.025$	$0.108 \pm 0.022$	$0.143 \pm 0.055$	0.0560
Si	8.15	$0.167 \pm 0.047$	$0.115 \pm 0.023$	$0.102 \pm 0.023$	$0.132 \pm 0.042$	0.0525
S	10.36	$0.049 \pm 0.016$	$0.056 \pm 0.013$	$0.051 \pm 0.014$	$0.051 \pm 0.021$	0.0316
Fe	7.87	$0.120 \pm 0.039$	$0.092 \pm 0.017$	$0.081 \pm 0.014$	$0.106 \pm 0.044$	0.0468

<sup>a</sup>The numbers denote averages of daily values with their  $1-\sigma$  variability. Photospheric (Phot.) values are from *Grevesse and Sauval [1998]*. SWICS, Solar Wind Ion Composition Spectrometer; FIP, first ionization potential.



# Measuring Ions in the Heliosphere



- Solar wind ions can be separated from non-solar ions via the following criteria
  - Charge states: PUIs are mostly singly charged
    - Once ionized (e.g, photoionization, charge exchange, electron impact), ions are quickly swept out via solar wind
  - Spatial distribution
    - Interstellar ion density depends on angle between spacecraft and interstellar flow direction
    - Density of solar wind ions falls off with distance from Sun
  - Velocity Distributions
    - Shown in previous slide
- PUIs discovered so far include
  - $H^+$ ,  $4He^+$ ,  $3He^+$ ,  $4He^{++}$ ,  $N^+$ ,  $C^+$ ,  $O^+$ , and  $Ne^+$ ,  $Mg^+$ ,  $Si^+$

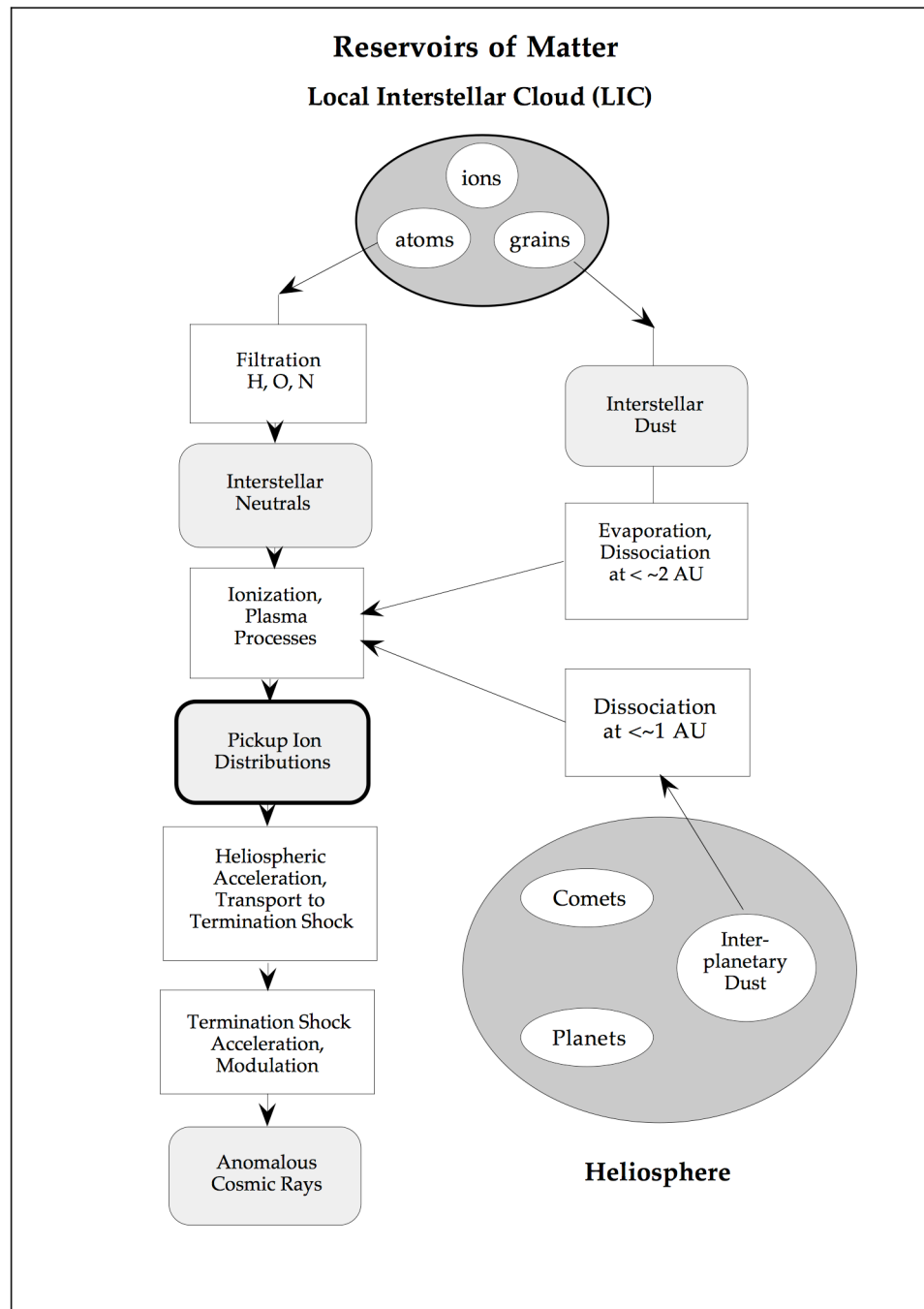
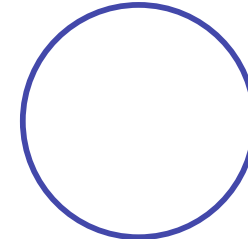
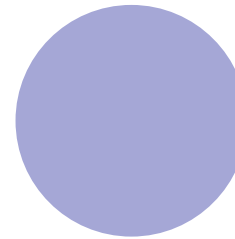


# Transport of IS material into the Heliosphere



- Interstellar neutrals from Local Interstellar Cloud (LIC) swept into the heliosphere at  $\sim 26$  km/s by motion of Sun
- H, O, N are filtered in the 100 - 200AU region beyond the heliopause (reduces density)
- Heliospheric magnetic field and termination shock deflects interstellar ions, only neutrals make it in
- Drag reduces the speed of atomic hydrogen by  $\sim 6$  km/s
- He, Ne penetrate deeper into the heliosphere due to higher ionization potential
- Both H and He are focused downstream of the Sun due to gravity (H, He focusing cones)

# Heliospheric Pickup Ions





# Significance of PUIs in the Heliosphere



- PUIs carry information regarding sources and dynamics of interaction processes in the solar wind
- Significant findings include
  - Established the elemental abundance in the LIC
  - Placed Limits on the magnetic field in the LIC
  - Allowed Inferences of the  $^3\text{He}/^4\text{He}$  ratio
  - Placed limits on the propagation properties of low-rigidity ions in solar wind
  - Discovery of a new population of PUIs
  - Observed cometary material
  - Observation of helium, hydrogen focusing cones



# Elemental Abundance in the LIC



- Can determine abundances without ambiguity from phase space density measurements (Gloeckler et al., 2001)

Termination Shock			LIC				Solar System Abundance Ratio
			Density (cm <sup>-3</sup> )				
Isotope	Ratio	Density (cm <sup>-3</sup> )	Atoms	Ions	Total	Ratio	
<sup>1</sup> H	7.5	0.115±0.015	0.2	0.04	0.24	10	10
<sup>4</sup> He	1	0.0153±0.0020	0.0153	0.009	0.024	1	1
<sup>3</sup> He	2.5×10 <sup>-4</sup>	(3.8±1.0) ×10 <sup>-6</sup>	3.8 ×10 <sup>-6</sup>	2.2×10 <sup>-6</sup>	6.0×10 <sup>-6</sup>	2.5×10 <sup>-4</sup>	-
<sup>14</sup> N	0.6×10 <sup>-3</sup>	(9.2±3.0) ×10 <sup>-6</sup>	1.1 ×10 <sup>-5</sup>	2.3×10 <sup>-6</sup>	1.3×10 <sup>-5</sup>	0.54×10 <sup>-3</sup>	1.12×10 <sup>-3</sup>
<sup>16</sup> O	4.5×10 <sup>-3</sup>	(6.9±1.7) ×10 <sup>-5</sup>	9.6 ×10 <sup>-5</sup>	2.1×10 <sup>-5</sup>	1.2×10 <sup>-4</sup>	5×10 <sup>-3</sup>	8.51×10 <sup>-3</sup>
<sup>20</sup> Ne	1.0×10 <sup>-3</sup>	(1.5±0.5) ×10 <sup>-5</sup>	1.5×10 <sup>-5</sup>	1.5×10 <sup>-5</sup>	3.0×10 <sup>-5</sup>	1.25×10 <sup>-3</sup>	1.23×10 <sup>-3</sup>

- 40% of LIC H is excluded from heliosphere
- 90% of LIC O penetrates in to the heliosphere
- Solar System Abundance for Ne is not well established



# Placed Limits on the magnetic field in the LIC



- Gloeckler et al. (1997) estimated LIC magnetic field via pressure balance
  - Bow shock at outer boundary of “filtration region”
  - Magnetic field is likely parallel to TS (Frish 1995)
  - TS at  $R > 80$  AU
  - Assumed LIC density is  $0.2 \text{ cm}^{-3}$
  - $V_H \sim 26 \text{ km/s}$
- Estimated value of magnetic field in LIC
  - $1.2 \text{ } \mu\text{G} > B_{\text{ISM}} < 4.3 \text{ } \mu\text{G}$  (close to observed value)



# Allowed Inferences of the $^3\text{He}/^4\text{He}$ ratio



- Only measurements of  $^3\text{He}/^4\text{He}$  in LIC from SWICS (high sensitivity)
- Places a new lower limit on missing matter in the universe (Gloeckler and Geiss, 1996, 1998a)
- $^3\text{He}$  production from stars less than predicted by some stellar evolution models
- $^3\text{He}/^4\text{He}$  ratio altered in solar system by nuclear burning making solar system sources inaccurate



# Propagation Properties of Low-Rigidity Ions



- PUIs have large mean free paths (MFPs)
- Presence of large number of PUIs below solar wind peak indicates that there is a large inward anisotropy
- Little pitch angle scattering of low rigidity PUIs occurs
- Turbulence in the heliosphere should yield smaller MFPs
- Reasons for this discrepancy could include
  - Pitch angle scattering suppressed at  $90^\circ$
  - Weak pitch angle scattering at all angles



# Discovery of a new population of PUIs



- Inside 1 AU, outgassing and ionization of interstellar grains, interplanetary grains, small comets, and grain collisions contribute to extended source
- Solar wind absorbed by dust and released again as slow neutrals or ions ( $\text{H}^+$ ,  $\text{C}^+$ ,  $\text{O}^+$ ,  $\text{N}^+$ ,  $\text{Ne}^+$ )
- This is the “inner source”
- PUIs injected within 10s of  $R_{\text{solar}}$
- PUIs undergo adiabatic focusing
- Ions also include  $\text{Mg}^+$ ,  $\text{Si}^+$ , ( $\text{CH}^+?$ ,  $\text{H}_2\text{O}^+?$ )
- $\text{C}^+/\text{O}^+ \sim 1$



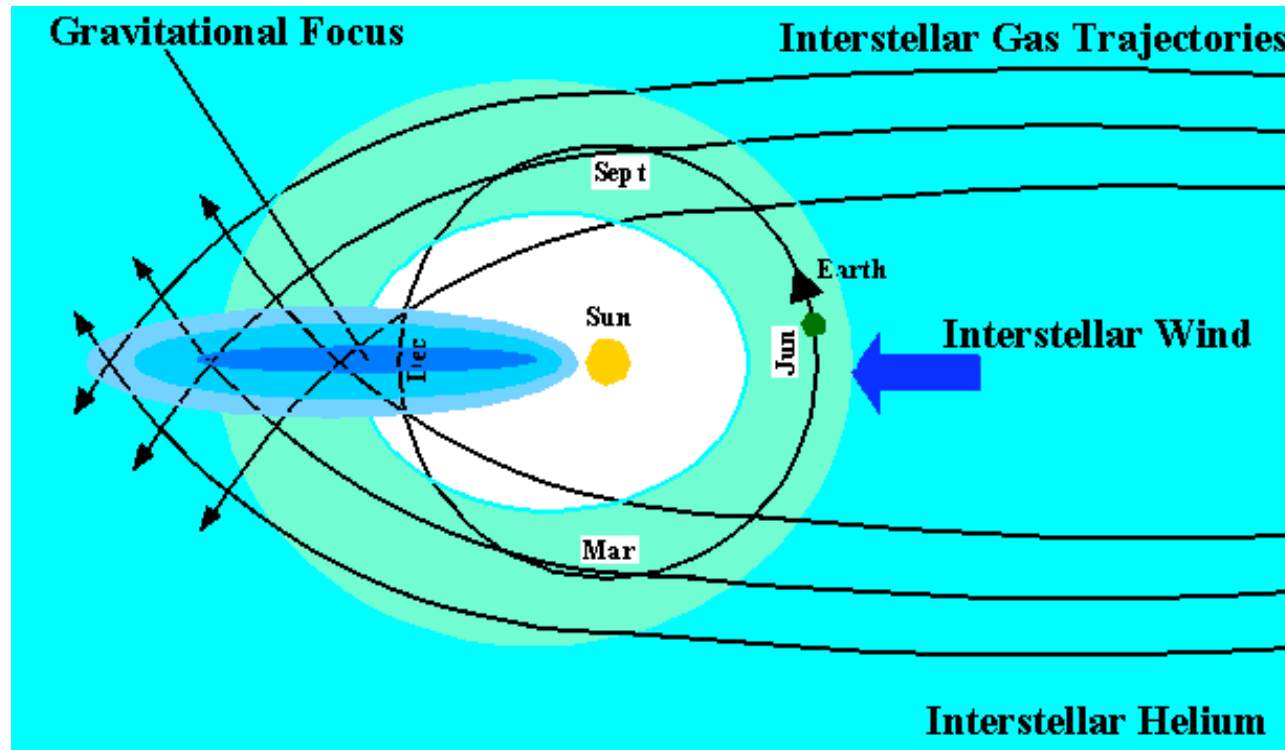
# Observed Cometary Material



- Comets are point sources of pickup ions
- As comet moves closer to the Sun, neutral gas is emitted at an increasing rate
- Produces tails in pickup ion populations extending to many AU
- Provide direct sampling of cometary composition



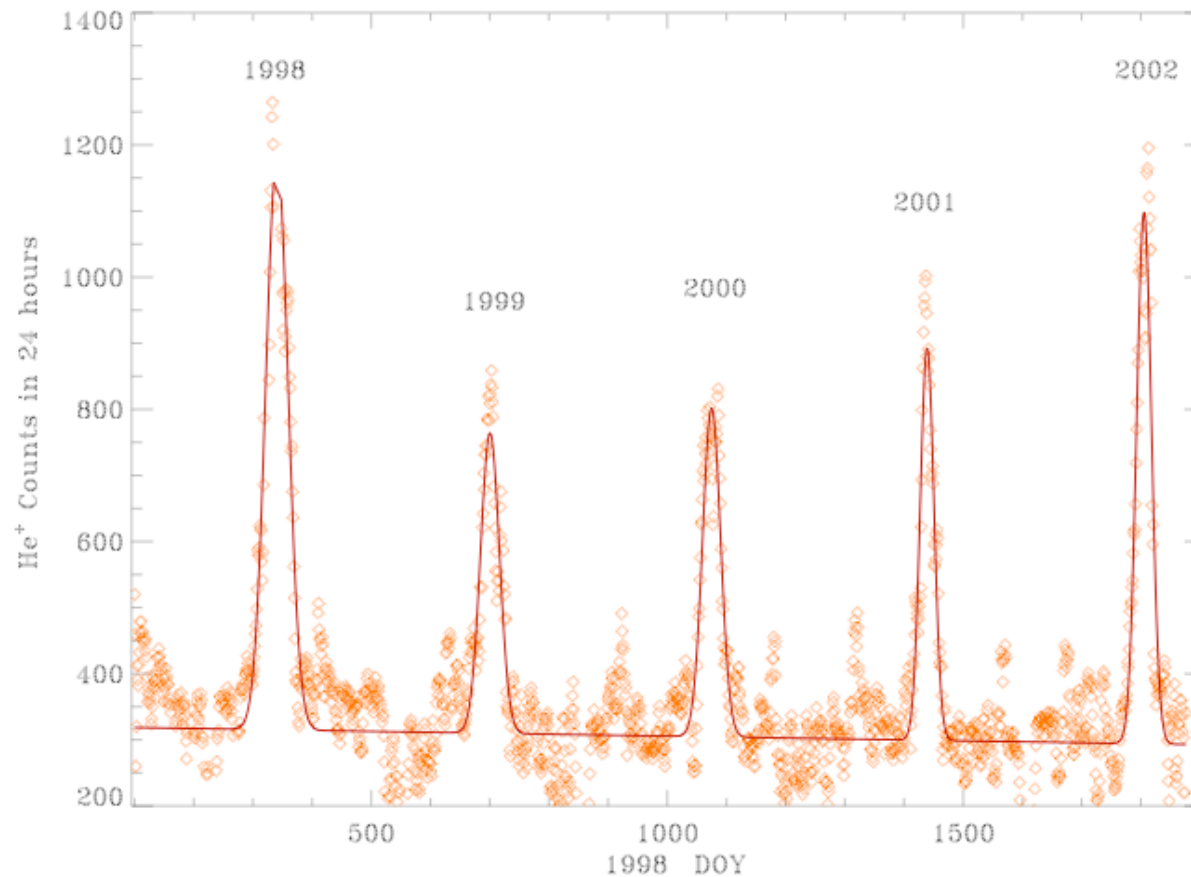
# Hydrogen and Helium Focusing Cones

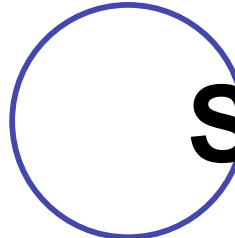
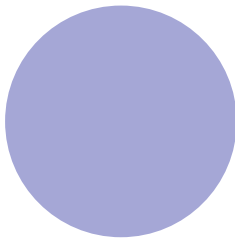


- He I that survives the ionization process is focused by the Sun's gravitational field on the downwind side  $\Rightarrow$  He cone

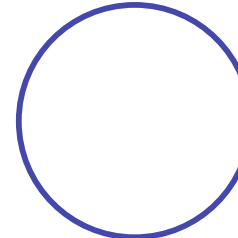
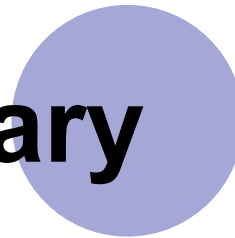


# Hydrogen and Helium Focusing Cones

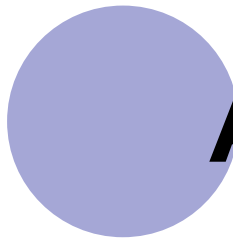




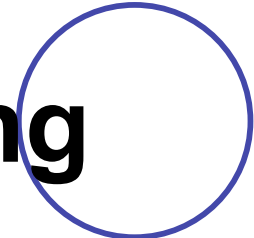
# Summary



- SWICS was originally designed to sample solar wind ions
- Ion mass spectrometers like SWICS on Ulysses and ACE also allow studies of PUIs
  - Direct sampling of the composition of interstellar gas and dust, interplanetary dust, cometary tails, etc.
  - Examination of dynamic processes involved in acceleration and propagation of PUIs.
- SWICS observations have yielded a wide variety of discoveries and insights into local interstellar and interplanetary space



# Additional Reading



Gloeckler, G., and J. Geiss, (1998), *Space Science Reviews*, 86, 127 (and references therein)

Gloeckler, G. et al., (1998) *Space Science Reviews*, 86, 497 (and references therein)

Kallenbach, R., et al., (2000) *Astrophysics and Space Science*, 274, 97 (and references therein)

Schwadron, N. A. and G. Gloeckler, (2007), *Space Science Reviews*, 130, 283 (and references therein)